GEORGES OVER PUERTO RICO

Reggina Garza and Jonathan Atwell

AUTHORS: Hydrologists, Southeast River Forecast Center (SERFC), National Weather Service, 4 Falcon Drive, Peachtree City, GA 30269
REFERENCE: *Proceedings of the 1999 Georgia Water Resources Conference*, held March 30-31, 1999, at the University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia

Abstract. Hurricane Georges, the second most deadly tropical storm of this past hurricane season, posed a unique forecasting problem to the Southeast River Forecast Center (SERFC). Though the SERFC has produced river forecasts for many hurricanes making landfall along the Gulf Coast and South Atlantic seaboard, this event was the first time the SERFC attempted to provide river guidance to Puerto Rico. Prior to this powerful storm's movement across the island, the SERFC provided forecasts on projected river response to the anticipated heavy rainfall. This paper will provide a case study on the results of these forecasts as compared to the actual river response as a result of observed rainfall associated with Georges. A comparison of actual precipitation amounts against forecasted rainfall is studied. Noteworthy river forecast model deficiencies are also discussed.

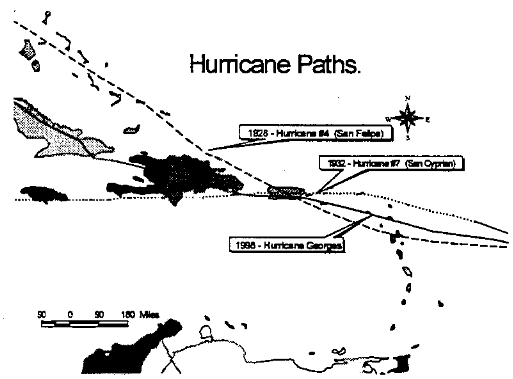

Figure 1. Hurricane paths, San Felipe (1928), San Cyprian (1932) and Georges (1998).

INTRODUCTION

On September 18, 1998, Tropical Storm Georges strengthened into a hurricane. This hurricane would later pass through Puerto Rico, the Dominican Republic, Haiti, Cuba, the Florida Keys, and eventually southern Mississippi. Hurricane Georges was directly responsible for more than 600 deaths and damage estimates in the United States alone have exceeded 5.1 billion dollars. Though the SERFC has produced river forecasts for many hurricanes making landfall along the Gulf Coast and South Atlantic seaboard, this event was the first time the SERFC attempted to provide river guidance to Puerto Rico. This paper will describe the storm track, the various inputs which are used within the National Weather Service River Forecast System (NWSRFS), the model's overall capabilities, and recommendations on the use of the NWSRFS when providing river guidance to Puerto Rico.

HURRICANE GEORGES

Georges passed through Puerto Rico from east to west. This track was similar to those of Hurricane # 4 in 1928 (Sept. 6-20) and Hurricane # 7 in 1932 (Sept. 25 - Oct. 3). Although several hurricanes have affected Puerto Rico, not since 1932 had the island been bisected by the path of one (Figure 1).

RAINFALL

The main area of rain associated with Hurricane Georges moved into Puerto Rico on Monday, September 21, 1998. At approximately 6:00 p.m. eastern daylight time (EDT), the heaviest rainfall was affecting eastern portions of the island. The heavy rain fell upon nearly saturated soils since the tropics were very active during the weeks leading up to the storm. This would likely produce fast runoff to river channels.

Many Puerto Rican river basins originate at higher elevations and flow downstream through urban areas. It was estimated it would take Georges about six to eight hours to move across Puerto Rico, with heavy rains occurring the entire time period. Basin average rainfall amounts of four inches were expected over the entire island, with even higher amounts likely to occur in the mountains.

Rainfall amounts in excess of 20 inches were reported; however, basin average rainfall amounts were much lower than these extreme reports (Figure 2). Basin averages are normally lower than point reports, unless it is a very uniform rainfall event. Mean Areal Precipitation (MAP) and Quantitative Precipitation Forecasts (QPF) are both basin average values. Both the MAP and QPF are used within the National Weather Service River Forecast System (NWSRFS) to simulate the response of a stream within a river basins.

NWSRFS AND PUERTO RICO

During 1997, the SERFC initiated hydrologic support for Puerto Rico. The NWSRFS was set up using 13 river basins across the island. These sites were selected by the Weather Service Forecast Office (WSFO) in San Juan based on the need to alert citizens of flash flood events. Daily Flash Flood Guidance (FFG) values were produced using the NWSRFS for these 13 locations. One of the calculations done within the NWSRFS is the evaluation of current soil moisture state within a given area. Soil moisture computations from the NWSRFS are used in the generation of FFG.

During Hurricane Georges, the SERFC used the NWSRFS to provide projected magnitudes of peak stage to each of the 13 river segments being monitored. This task was complicated by the fact that the predicted timing and magnitude of the river stages in the region are questionable because of the extremely fast reaction of these rivers. See Figure 3 and Table 1 for the location and drainage areas of these 13 forecast sites.

Table 1. River Basin Drainage Areas (sq. mi.)

Basin	Site ID	Drainage Area
Caguas	CAGP4	89.8
Gurabo	GURP4	60.2
Comerio	COMP4	109.0
Ciales	CIAP4	128.0
Hormigueros	HORP4	120.0
Coamo	COAP4	43.5
Arecibo	AREP4	200.0
San Sebastian	SEBP4	134.0
Moca	MOCP4	71.2
Hato Rey	RPOP4	15.4
Vega Baja	VGBP4	99.1
Toa Alta	TOAP4	208.0
Manati	MANP4	197.0

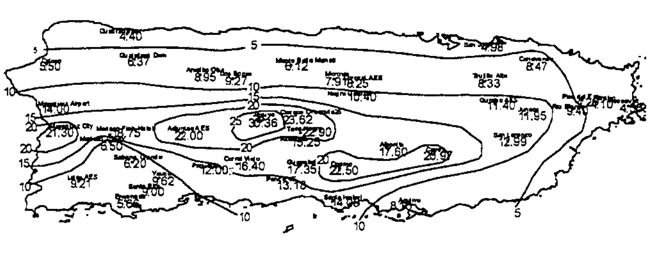

Figure 2. Rainfall totals for Puerto Rico.

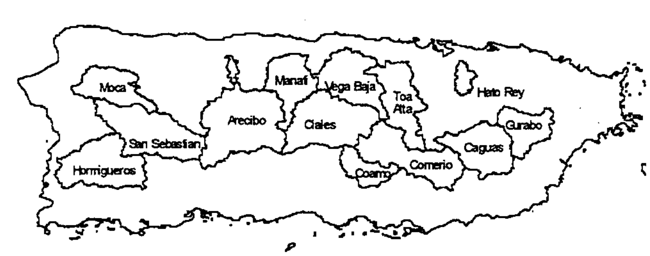

Figure 3. Location of forecast basins.

OVERVIEW OF NWSRFS INPUTS

Three main inputs are used to produce a river forecast simulation: existing soil moisture, the addition of new measured rainfall, and an educated guess of what future rain will fall within the river basin.

Soil Moisture

The SERFC uses the Sacramento Soil Moisture Accounting Model (SAC-SMA) to simulate the response to streams. This rainfall/runoff model breaks the soil surface down into three portions: a pervious portion, an impervious portion, and a variable impervious portion. The **pervious portion** has two layers, the upper zone and the lower zone. The upper zone is the source of most storm runoff and is therefore the active, permeable soil. The lower zone is a deeper soil layer and is the source of baseflow runoff. Both these layers contain tension (hydroscopic) water, which is removed only by evaporation, and free water (gravity and capillary), which moves vertically and horizontally through the soil. The **impervious portion** accounts for impervious surfaces connected to the river channel, such as roads and buildings. The **variable impervious portion** is an area directly connected to the river channel that turns impervious once it becomes saturated.

The SAC-SMA uses sixteen different parameters to simulate the interaction between the three portions of the soil surface. The sixteen parameters are calibrated using historical precipitation and streamflow values. The results of the calibration are then used in the operational SAC-SMA.

Mean Areal Precipitation

The precipitation network which the SERFC uses to calculate mean areal precipitation predominately comprises of stations which report only once a day. A few locations report precipitation every 6 hours, and even fewer on an hourly basis. The stations which report only a 24-hour precipitation total are broken down into four 6-hour time periods. This is accomplished by using stations which are able to report precipitation on an hourly or 6-hourly basis. These reports provide the key to when the rainfall occurred. Once the data is in 6-hour intervals, the reporting stations located within a river basin, and some that are nearby, are averaged. Theissen weighting is used to produce the basin average rainfall. This average is the mean areal precipitation value or MAP.

Quantitative Precipitation Forecasts

QPF is issued twice daily by the WSFO in San Juan and is incorporated within the hydrologic model at the SERFC. This data is also broken into four 6-hour periods, producing a 24-hour forecast of basin average rainfall. This QPF product provides 24-hour precipitation totals for each of the 13 river basins defined in the SERFC's river model. Table 2 displays an example of a QPF product from Puerto Rico.

EVALUATION OF QPF/MAP

The WSFO in San Juan began issuing QPF to the SERFC in 1997. Hurricane Georges was the first excessive rainfall event to effect the island since this duty was implemented. Forecasting precipitation amounts for a land falling hurricane is a very difficult undertaking. Differences in forward speed and storm track could significantly affect the amount of heavy rain on the island.

A day before landfall, QPF issued from this office conveyed a strong confidence that greater than six inches of rain would fall across the island over the next 24 hours. As Hurricane Georges closed in on the island, forecasts of basin average rainfall exceeded 11 inches over 24 hours.

The difference between the QPF's and the MAP's produced during Georges, for each of the 13 river segments defined in the forecast model, is presented in Figures 4(a-o). New QPF's were issued by the WSFO in San Juan every 12 hours, so the values evaluated were always for the first two 6-hour periods.

When viewing the figures, positive values for the difference indicate that the forecast precipitation was too high, while negative values indicate it was too low. During this event, the highest rainfall forecast for any 6-hour period was 3.0 inches. The mean areal precipitation values computed for most of the river basins were higher values. This information confirms that the QPF during the time period that Georges moved through Puerto Rico (00Z-06Z) was too low. Another noticeable trend from these graphs is the continued forecast of heavy rainfall even after Georges moved through Puerto Rico. Both of these trends are very common when forecasting mean areal rainfall during heavy rain events.

RFC GUIDANCE LEADING INTO GEORGES

On September 21, once it was apparent that Georges was going to impact Puerto Rico, the SERFC produced scenarios to project anticipated river response to both 6 and up to 9-inch basin average rainfall events. These contingency forecasts can easily be executed at the SERFC. The results of these contingency runs can quickly be conveyed to the WSFO and emergency managers. Planning for additional staffing and possible emergency planning are actions which can be carried out as a result of these contingency forecasts.

The first scenario, which included a total rainfall of 6 inches, was issued to the WSFO in San Juan the morning of September 21. This amount was evenly distributed across the island, falling in two 6-hour time periods.

River Basin	Amount	Time Period
All Basins	1.0 inch	8:00 a.m. to 2:00 p.m. EDT
	5.0 inch	2:00 p.m. to 8:00 p.m. EDT

Table 2. Example of a QPF Product.

```
Routine QPF
National Weather Service Forecast Office SAN JUAN, PR
1045 UTC 09/22/98

.B SJU 980922 Z DH12 /DC9809221045
.B1 /DRH+06/PPQFZ /DRH+12/PPQFZ /DRH+18/PPQFZ /DRH+24/PPQFZ
.B2 /DRH+24/PPDFZ
:
:         6-hr  6-hr  6-hr  6-hr 24-hr
:         pcpn  pcpn  pcpn  pcpn  pcpn
:         endg  endg  endg  endg  endg
:          18Z   00Z   06Z   12Z   12Z
:        09/22 09/23 09/23 09/23 09/23
:
AREP4    3.00/ 2.71/ 2.62/ 1.07/ 9.40/ :ARECEBO, PR
CAGP4    3.00/ 2.98/ 1.30/ 1.40/ 8.68/ :CAGUAS, PR
CIAP4    3.00/ 2.73/ 2.68/ 1.28/ 9.69/ :CIALES, PR
COAP4    3.00/ 3.00/ 3.00/ 1.50/10.50/ :COAMO, PR
COMP4    3.00/ 2.94/ 2.84/ 1.50/10.28/ :COMERIO, PR
GURP4    2.96/ 2.91/ 0.64/ 0.76/ 7.27/ :GURABO, PR
HORP4    3.00/ 3.00/ 3.00/ 1.33/10.33/ :HORMIGUEROS, PR
MANP4    3.00/ 1.75/ 1.76/ 0.64/ 7.15/ :MANATI, PR
MOCP4    3.00/ 3.00/ 2.67/ 0.67/ 9.34/ :MOCA, PR
RPOP4    1.96/ 1.28/ 0.79/ 0.57/ 4.60/ :HATO REY, PR
SEBP4    3.00/ 3.00/ 3.00/ 1.27/10.27/ :SAN SEBASTIAN, PR
TOAP4    2.89/ 1.64/ 1.45/ 0.81/ 6.78/ :TOA ALTA, PR
VGBP4    3.00/ 1.19/ 1.24/ 0.56/ 5.99/ :VEGA BAJA, PR
```

The second scenario, issued the evening of September 21, included up to 9 inches of basin average rainfall during an 18-hour span.

River Basin	Amount	Time Period (Sept. 21 through Sept. 22)
AREP4, CAGP4, CIAP4, COMP4, GURP4, MANP4, RPOP4, TOAP4, VGBP4		
	5.0 inch	8:00 p.m. to 2:00 a.m. EDT
	3.0 inch	2:00 a.m. to 8:00 a.m. EDT
	0.5 inch	8:00 a.m. to 2:00 p.m. EDT
COAP4		
	3.0 inch	8:00 p.m. to 2:00 a.m. EDT
	5.0 inch	2:00 a.m. to 8:00 a.m. EDT
	1.0 inch	8:00 a.m. to 2:00 p.m. EDT
MOCP4, SEBP4, HORP4		
	3.0 inch	8:00 p.m. to 2:00 a.m. EDT
	5.0 inch	2:00 a.m. to 8:00 a.m. EDT
	0.5 inch	8:00 a.m. to 2:00 p.m. EDT

The results of these contingency forecasts as compared to the reported peak stages are listed on Table 3. Most of the rivers rose and had crested before 7:00 a.m. EDT on September 22, 1998. This rapid response was due to the extremely heavy rain from Hurricane Georges, the size of the river basins, topography, and the existing wet soil conditions just prior to the event. Table 4 depicts the fast rising nature of these streams due to the excessive tropical rainfall.

RESULTS AND CONCLUSIONS

After examining the QPF products issued during Hurricane Georges, it was concluded that the QPF was too low for the time periods in which the heaviest rainfall actually occurred. The maximum forecast of rainfall during any 6-hour time period was never higher than 3 inches. Therefore, the scenarios modeled by the SERFC were more realistic than the

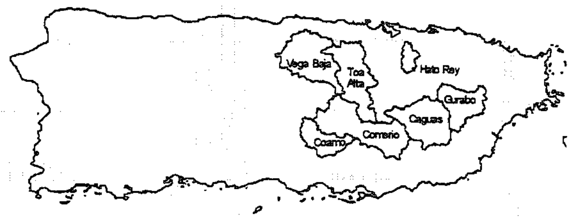

Figure 4a. River Basin Locations

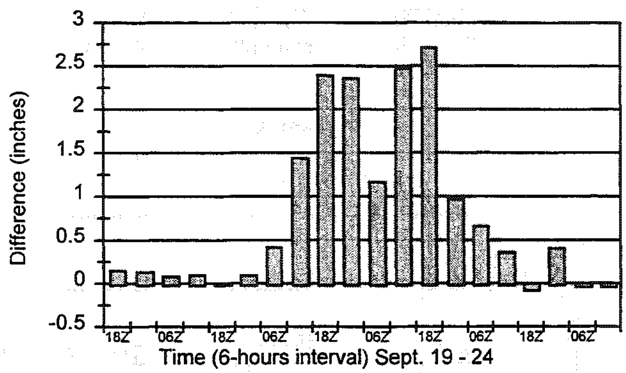

Figure 4b. Vega Baja

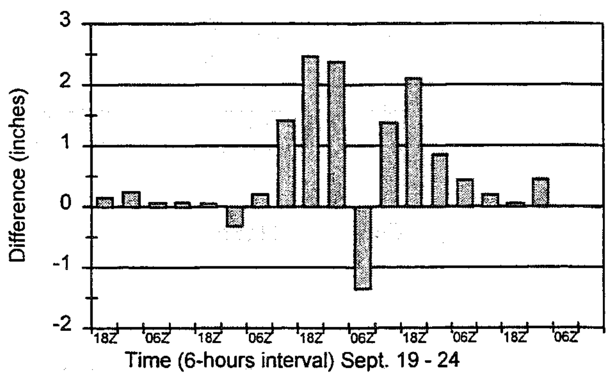

Figure 4c. Toa Alta

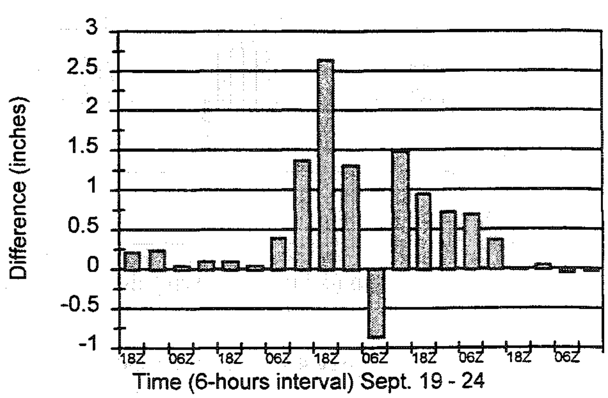

Figure 4d. Hato Rey

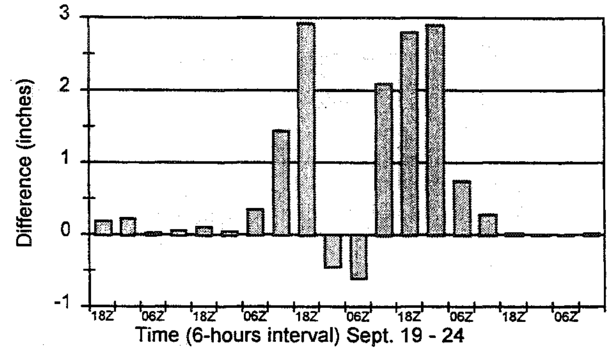

Figure 4e. Gurabo

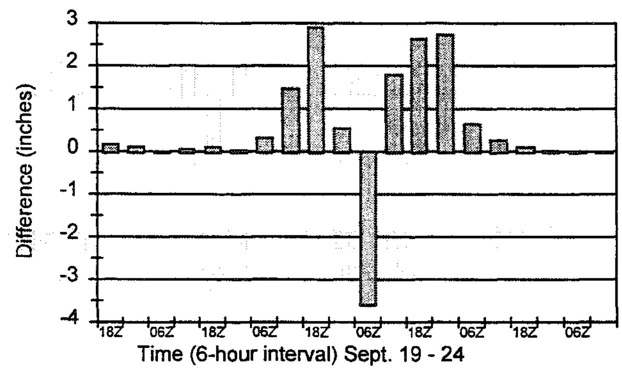

Figure 4f. Caguas

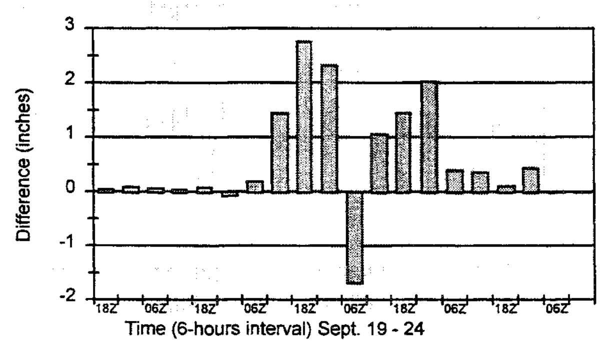

Figure 4g. Comerio

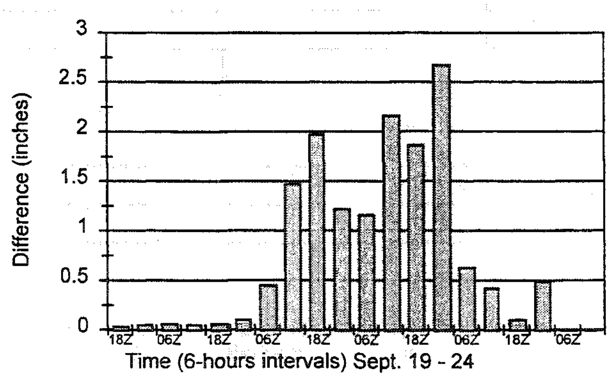

Figure 4h. Coamo

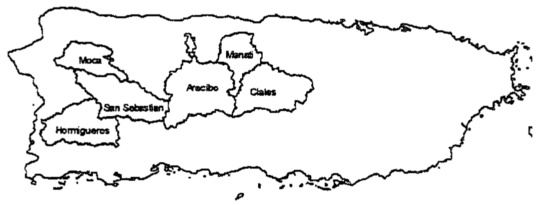

Figure 4i. River Basin Locations

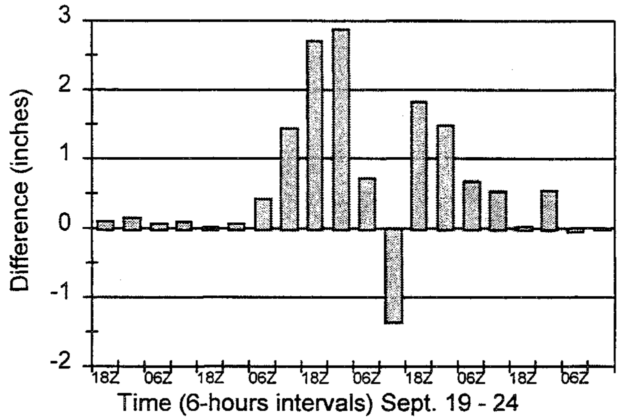

Figure 4j. Manati

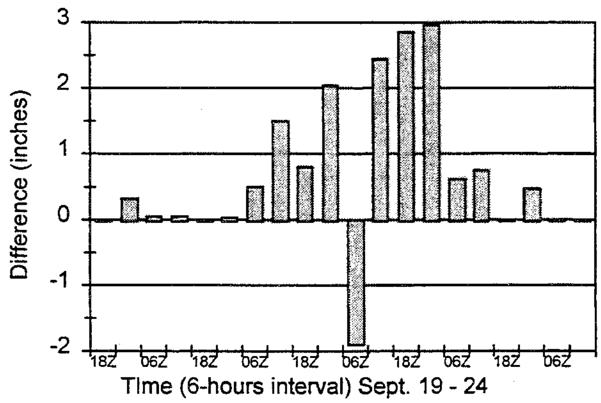

Figure 4k. Moca

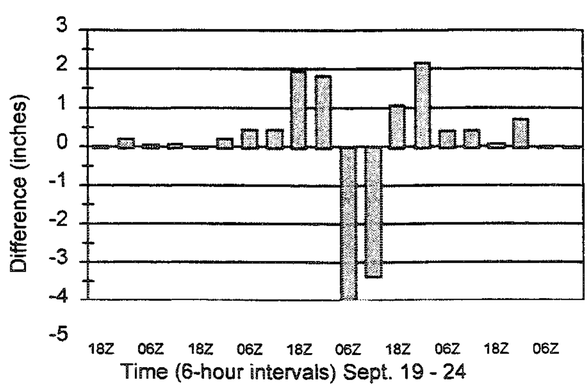

Figure 4l. Arecibo

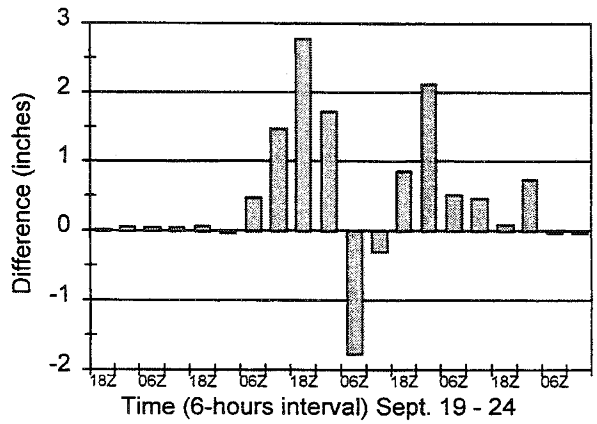

Figure 4m. Ciales

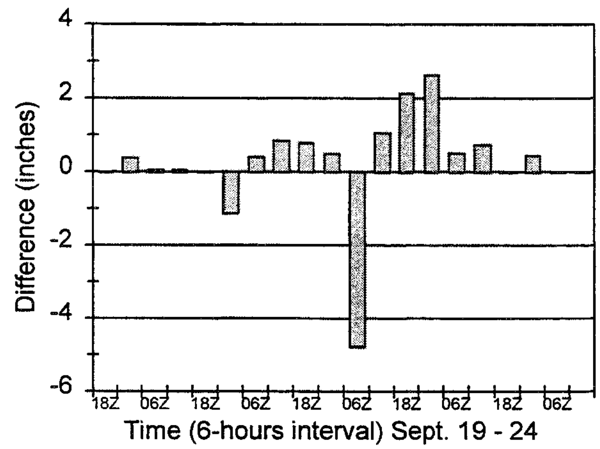

Figure 4n. Hormigueros

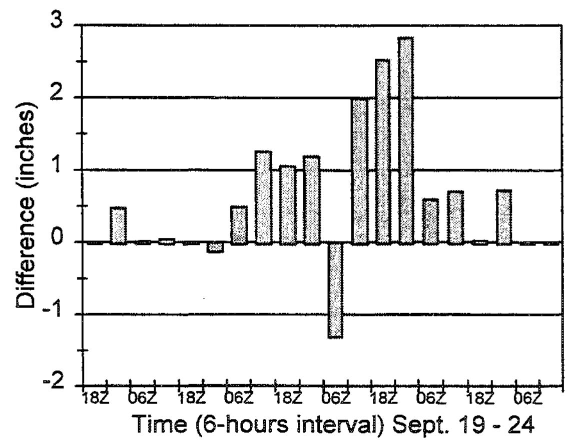

Figure 4o. San Sebastian

Table 3. Peak Stages at Forecast Sites.

Station ID Flood Stage(ft)	Scenario 1 Peak Elevation (ft.) Day and Time	Scenario 2 Peak Elevation(ft.) Day and Time	Crest Peak Elevation (ft.) Day and Time	Model Performance
CAGP4 17	21 9/21 at 8 p.m.	21 9/22 at 2 a.m.	14.55 9/21 at 10 p.m.	Over
GURP4 19	24 9/22 at 2 a.m	25 9/22 at 8 a.m.	28.84 (High Water Mark)	Under
RPOP4 12	19 9/21 at 8 p.m.	19 9/22 at 2 a.m.	17.64 9/21 at 10 p.m.	O.K.
COMP4 12	19 9/21 at 8 p.m.	18 9/22 at 2 a.m.	24.67 9/21 at 11:30 p.m.	Under
TOAP4 17	22 9/22 at 2 a.m	22 9/22 at 2 p.m.	25.58 9/22 at 4 a.m	Under
COAP4 12	15 9/21 at 8 p.m.	16 9/22 at 8 a.m	11.26 (Crest Stage Gage)	Over
VGBP4 16	18 9/22 at 2 a.m	18 9/22 at 2 p.m.	16.55 9/22 at 6 p.m.	O.K.
CIAP4 13	13 9/21 at 8 p.m.	13 9/22 at 8 a.m	22.38 (High Water Mark)	Under
MANP4 26	30 9/22 at 8 a.m	30 9/22 at 2 p.m.	34.77 9/22 at 3:30 a.m	Under
AREP4 13	19 9/21 at 8 p.m.	20 9/22 at 2 a.m.	17.39 9/22 at 7 a.m.	O.K.
HORP4 23	26 9/22 at 2 a.m	21 9/22 at 8 a.m	28.01 9/22 10:30 a.m	Under
SEBP4 11	19 9/21 at 8 p.m.	27 9/22 at 2 p.m.	29.00 9/22 at 3 a.m	Under
MOCP4 20	27 9/21 at 8 p.m.	20 9/22 at 8 a.m	35.00 9/22 at 7 a.m	Under

Over -- means model overestimated the peak
Under -- means model underestimated the peak
O.K. -- means model simulated the peak within 1.5 ft.

Table 4. Maximum Water Level Rises for a 2- Hour Period at Selected Sites

Station ID	Maximum Rises (feet)	Time Interval	Date
AREP4	9	2 to 4 a.m.	September 22nd
CAGP4	6	8 to 10 p.m.	September 21st
CIAP4	11	8 to 10 p.m.	September 21st
MANP4	19	12 to 2 a.m	September 22nd
HORP4	5 (estimated)	2 to 4 a.m.	September 22nd
COMP4	17	9 to 11 p.m.	September 21st
TOAP4	15	12 to 2 a.m.	September 22nd
MOCP4	12	12 to 2 a.m.	September 22nd
RPOP4	6	8 to 10 p.m.	September 21st
SEBP4	20	1 to 3 a.m.	September 22nd
VGBP4	5	4 to 6 a.m.	September 22nd

actual QPF. Examining scenario #1, the closest to what actually occurred, it was found that the hydrologic model (NWSRFS) under-simulates. This was determined by looking at the difference between actual peak stage reports and what the model simulated. This difference can partly be explained by the time discretization used in the model. Based on the results of the forecast, it can be concluded that there are limitations in using NWSRFS to forecast fast rising rivers. In general, forecast timing will be off in fast responding rivers because of the 6-hour intervals being used in NWSRFS. NWSRFS's time discretization is the main limitation for this type of hydrologic environment.

Recently, with the use of an Interactive Forecast Program (IFP), data can be viewed in time intervals as short as 1 hour. Although this is helpful in viewing river trends, the forecasting time period remains unchanged and all the computations within NWSRFS remain on the 6-hour time step. After examining this tropical event, it was clear that these rivers can experience large variations of stage in only 2 hours (Table 4), thus they can crest and recede within one time step of the simulation (Figure 6).

The time intervals for computations of MAP and QPF are currently set at 6 hours within the NWSRFS. This means that even if precipitation data was available in 1-hour intervals, the MAP would still be computed for a 6-hour time interval. To simulate a scenario that considers heavy rainfall in a shorter period, this would still be inputted as a 6-hour QPF. The use of the larger time increment will smooth and average the intensity of a rain event. If an event produces 2 inches of rain in 1 hour, this would have to be simulated in NWSRFS as 2 inches in a 6-hour interval. The use of a unit hydrograph within NWSRFS will determine the time distribution of the runoff, but because we must use a 6-hour unit hydrograph, timing will only be as accurate as plus or minus 6 hours. In a fast responding river, this translates into zero timing accuracy.

Unit hydrographs with short durations have higher peaks than those with longer durations. The 6-hour unit hydrograph used in the NWSRFS will result in a smoother peak, which will occur later in time, than to a 1-hour unit hydrograph (Figure 7).

Therefore, as a result of averaging rainfall over a 6-hour time step and the associated use a 6-hour unit hydrograph, the stage forecast issued will generally be underestimated, especially during heavy precipitation events.

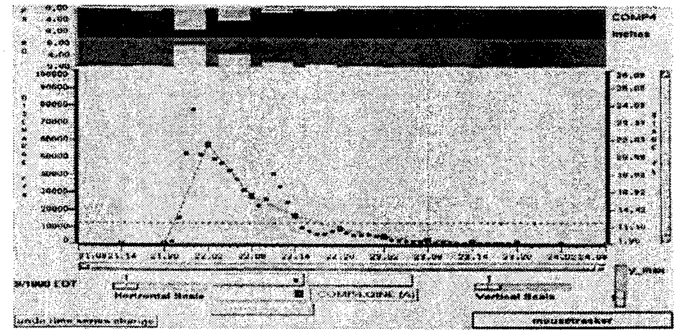

Figure 6. Output from IFP, Hourly Stage Data.

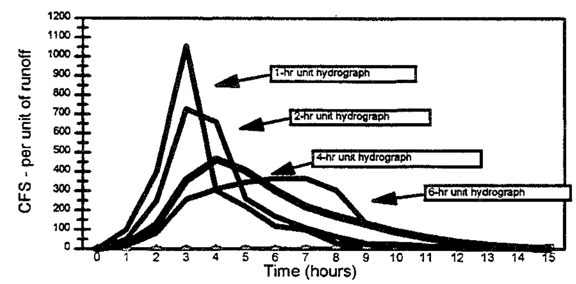

Figure 7. Unit hydrograph comparisons

RECOMMENDATION

Significant time has been spent in calibration of the Puerto Rico river forecast sites. Further calibration using the 6-hour time step would not significantly improve forecast results. In rivers of this nature, a site specific model with time intervals of 1 to 3 hours would be more appropriate than using NWSRFS. The National Weather Service WFO Hydrologic Forecast System (WHFS) could be the answer. In the meantime, until a site-specific model is developed, the NWSRFS is a tool that can provide a rough order of magnitude of peaks. It needs to be understood that timing and accuracy may have significant errors due to 6-hour time interval calculations.

In addition to NWSRFS continually computing the soil moisture conditions, the FFG must continue to be produced daily. By running different precipitation scenarios, NWSRFS can be used for planning purposes. These contingency runs can easily be executed and the result quickly conveyed to the WSFO and emergency managers.

Some improvements are also needed for QPF products from the WSFO. During major tropical events, the forecast precipitation should be more concentrated within the given time intervals.

The use of NWSRFS on a one-hour time step would greatly aid the river guidance to Puerto Rico. In the future, it is planned for NWSRFS to be able to use a one-hour time step.

References

Cry, G.W., W.H Haggard, H.S. White, 1959. North Atlantic Tropical Cyclones. U.S. Department of Commerce, Weather Bureau.

Linsley , R.K., M.A. Kohler, J.L.H Paulhus, 1982. *Hydrology for Engineers*. pp 214-230.